A NEXT GENERATION LIGHT SOURCE FACILITY AT LBNL*

J.N. Corlett#, B. Austin, K.M. Baptiste, J.M. Byrd, P. Denes, R. Donahue, L. Doolittle, R.W. Falcone, D. Filippetto, S. Fournier, D. Li, H.A. Padmore, C. Papadopoulos, C. Pappas, G. Penn, M. Placidi, S. Prestemon, D. Prosnitz, J. Qiang, A. Ratti, M. Reinsch, F. Sannibale, R. Schlueter, R.W. Schoenlein, J.W. Staples, T. Vecchione, M. Venturini, R. Wells, R. Wilcox, J. Wurtele, LBNL, Berkeley, CA94720, U.S.A.
A. Charman, E. Kur, UCB, Berkeley, CA 94720, U.S.A.
A.A. Zholents, ANL, Argonne, IL, 60439, U.S.A.

Abstract

The Next Generation Light Source (NGLS) is a design concept, under development at LBNL, for a multi-beamline soft x-ray FEL array powered by a ~2 GeV superconducting linear accelerator, operating with a 1 MHz bunch repetition rate. The CW superconducting linear accelerator is supplied by a high-brightness, high-repetition-rate photocathode electron gun. Electron bunches are distributed from the linac to the array of independently configurable FEL beamlines with nominal bunch rates up to 100 kHz in each FEL, and with even pulse spacing. Individual FELs may be configured for EEHG, HGHG, SASE, or oscillator mode of operation, and will produce high peak and average brightness x-rays with a flexible pulse format, with pulse durations ranging from sub-femtoseconds to hundreds of femtoseconds.

OVERVIEW

The NGLS is being designed to operate in a novel parameter regime, providing a suite of unique features compared to existing or planned X-ray light sources, including most notably a high-repetition-rate (1 MHz), high-brightness electron source, and a SCRF electron linac operating in CW mode which will provide bunches at high average beam power with uniform bunch spacing [1, 2]. These bunches will be distributed via a spreader system to an array of independently configurable FELs, each operating at three or more orders-of-magnitude higher pulse repetition rates than existing X-ray FELs, and each with adjustable photon pulse power, central wavelength, polarization, and ultrafast temporal resolution down into the attosecond regime. Our baseline design for a set of three simultaneously operable X-ray beamlines will serve a large number of experiments per year, with the capability of providing up to ~100 W of average power to each of six end-stations (two per FEL), with tunability spanning the important absorption edges of carbon, oxygen, nitrogen and the L-edges of the first-row transition metals (i.e., to 1.2 keV in the fundamental, and higher in the 3rd harmonic). While the highly successful low-repetition-rate X-ray FELs provide orders-of-magnitude improvement, primarily in peak power and temporal resolution, compared to third-generation synchrotron sources, peak power is not a substitute for the level of average power and/or coherent power that will be provided by NGLS.

* Work supported by the Director, Office of Science, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231
# jncorlett@lbl.gov

FEL PERFORMANCE

The primary spectral range of the NGLS baseline design will extend from 280 eV to 1.2 keV at the fundamental of the undulator emission (using undulators with different periods) and up to approximately 3 keV at much reduced intensity with the generation of harmonics. Lower photon energies might be reached by extracting some electron bunches at lower energy. Flux may be controlled from about 10^8 to about 10^{12} photons per pulse in the fundamental, depending on the desired wavelength, pulse duration, and repetition rate. Laser seeding will be implemented to produce pulses with duration as short as 250 attoseconds, with temporal coherence approaching fundamental transform limits, with the possibility of some control over chirp or longitudinal pulse-shape, and with synchronization of the X-ray pulses to end-station lasers with femtosecond precision. One of the two seeded FELs will be capable of producing “two-color” X-ray pulses, while the other seeded FEL will provide better energy resolution with longer pulses and high temporal coherence. The third FEL will be a non-seeded SASE device capable of operating at the full repetition rate of the linac, thereby providing very high average power X-ray beams. At approximately constant average electron beam power, we can operate at a higher pulse repetition rate using bunches of lower charge, shorter duration, but higher brightness. These bunches might enable lasing at shorter wavelengths, or possibly the operation of a SASE beamline in so-called “single-spike” configuration, with each short electron pulse naturally radiating into at most a very few longitudinal modes.

MACHINE LAYOUT

Figure 1 shows the main machine components. Bunches with the required high brightness will be generated at the desired high repetition rate by a state-of-the-art VHF electron photo-gun, and will undergo emittance compensation and compression by ballistic and velocity bunching through the injector. Further compression will occur through a magnetic chicane in the linac before acceleration to the final beam energy.

The machine is designed for an average current capability up to 1 mA, beyond our initial parameters of 300pC and 1MHz but consistent with a wide range of bunch charge and time structures. We note that beam brightness can be increased at lower bunch charge, and the gun and linac can accommodate a wide variety of

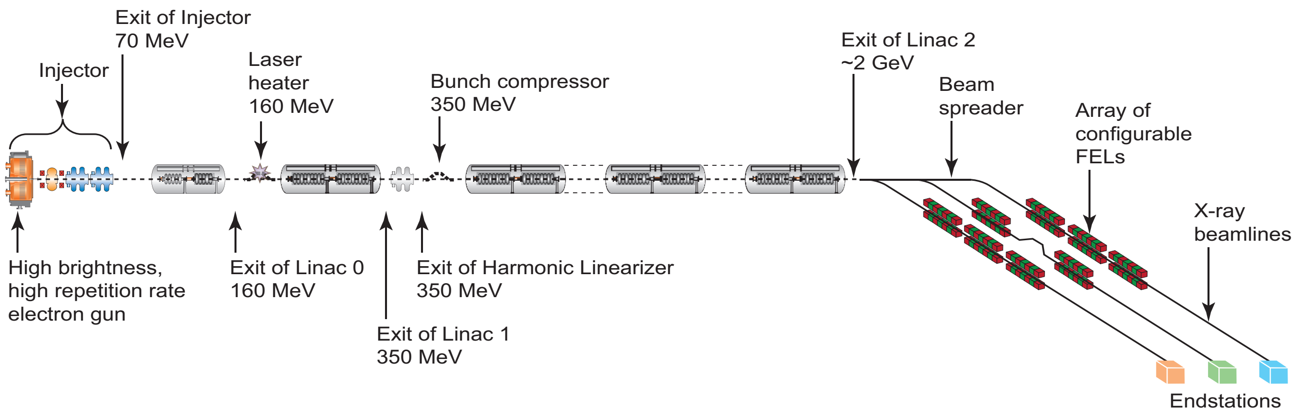

Figure 1: Schematic layout of the main components of the NGLS (not to scale).

conditions, including operation with low-charge, high-brightness, ultra-short bunches for SASE-based, ultra-fast X-ray production. Our baseline design has been developed assuming a bunch charge of 300 pC, and allows flexibility to increase versatility in performance. Higher charge operation is anticipated for longer pulse durations, or for higher peak current to improve efficiency of photon production. Further studies will be required to delimit the exact boundaries of the beam parameter-space accessible by the NGLS.

The maximum electron beam energy of approximately 2 GeV has been chosen in our baseline design so as to be able to produce 1.2 keV (1 nm) photons with readily available undulator technology (periods of about 18 mm, and minimum K-values of 0.8), but with a minimal accelerator footprint and cost.

Injector

The injector chain begins with a photocathode installed in a 187 MHz RF electron gun operating in CW mode, and a drive laser. A "bucking" solenoid integrated into the gun controls the magnetic field at the cathode surface. The next elements are a solenoid followed by a buncher cavity and then by a second solenoid. These elements initiate emittance compensation while simultaneously performing "ballistic" bunch compression. The next element is a cryostat containing a single 1.3 GHz, CW, TESLA-like, superconducting 9-cell cavity.

This superconducting cavity accelerates the beam from 750 keV at the gun exit and performs velocity bunching by de-phasing the RF with respect to the maximum acceleration phase. Downstream from this cryostat, another room-temperature solenoid continues the emittance compensation process and allows for the control of the transverse beam size in the remaining sections of the injector. The last element in the injector is a second cryostat containing five 1.3 GHz CW TESLA-like superconducting 9-cell cavities. The energy at the exit of the injector is about 70 MeV.

The photoinjector is designed to operate at 1 MHz repetition rate and up to 1 nC pulse charge, or possibly at higher repetition rate but correspondingly lower charge. The optimal way to achieve this design goal is to use high quantum efficiency (QE) cathode materials. We are assessing positive-electron-affinity semiconductor photocathodes such as cesium telluride (Cs_2Te) as used at FLASH, and di-potassium cesium antimonide (K_2CsSb). Both cathodes offer initial QEs significantly higher than 5% with photoemission in the UV for Cs_2Te and in the visible for the K_2CsSb. The photocathode laser will be a commercial 1.5 µJ, 1030 nm, 0.6 ps system, with crystal-based harmonic generation to 515 and 257.5 nm for the two types of cathodes. The laser is frequency stabilized and can be locked to the RF frequency, or used as a primary clock itself for commissioning. Status of the gun is described in [3–6].

Linac

Designed to accept electron bunches at about 70 MeV energy from the injector, the linac provides acceleration up to ~2 GeV before directing the beam to the spreader for distribution into the separate FEL undulator lines.

The proposed layout, based on the preliminary choice of TESLA-like superconducting cavity technology, consists of six main sections. The first section, Linac 0, interfaces the linac with the injector, provides about 90 MeV acceleration, and accommodates the diagnostics stations needed to monitor the beam phase space before its entrance into the "laser heater." The laser heater is intended for control of the beam's uncorrelated energy spread and for stabilization of the beam dynamics. The beam is then further accelerated in Linac 1 (with 225 MeV energy gain), conditioned by passage through a 3.9 GHz third-harmonic RF structure, compressed through a single-chicane bunch compressor at about 350 MeV energy, and then accelerated to the final energy by Linac 2, the last linac section. Given the 30-50 A range for the beam peak current out of the injector, a 10-17 compression factor is required in the linac. The lattice design includes beam collimators placed in the bunch compressor and at various locations along Linac 2 in correspondence to the local maxima of the betatron functions, and additional shielding will be employed in these areas. Further discussion of the linac design can be found in [7].

FELs

The NGLS design incorporates multiple FEL beamlines, each of which will deliver X-ray beams with distinctive photon attributes, as to energy, pulse duration, bandwidth, polarization, photon flux, synchronization, and pump-probe capabilities. Typically a single beamline will span a range of 3-5 in photon energy, depending on the undulator parameters and technology. The three initially proposed beamlines are:

- Beamline 1: A seeded beamline using the EEHG seeding scheme [8] with two laser-driven modulators to generate highly upshifted photons. The pulses can have a duration ranging from 5 to 150 fs. producing close to transform-limited pulses
- Beamline 2: A seeded two-color X-ray, ultrashort-pulse beamline using a variant of the EEHG seeding scheme, produces two sub-femtosecond pulses, each ~250 as duration [9]. The wavelength of each pulse can be independently controlled, and the time delay between the two pulses can be controlled with a precision comparable to the duration of each pulse.
- Beamline 3: A SASE beamline and needs no external seed laser. This beamline has a more robust design and can operate at the full 1 MHz electron bunch repetition rate, and potentially greater.

Figure 2 shows the nominal flux in each of the three FELs, as a function of wavelength tuning, for the baseline machine, and electron beam parameters listed in Table 1.

The two seeded beamlines are capable of operating at up to 100 kHz repetition rate, whereas the SASE beamline may operate at the full machine repetition rate. Each beamline will cover a wavelength range from about one to a few nanometers, but the eventual complete range of photon energies accessible by the overall facility could be considerably larger than this. Further discussion of the FEL configurations can be found in [10].

Timing and Synchronization

The NGLS will require an exacting level of synchronization between accelerator sub-systems, user and accelerator laser systems, and diagnostics in order to achieve both the desired electron and X-ray beam performance and to enable time-resolved optical pump/X-ray probe studies with femtosecond or better resolution. LBNL staff are developing timing distribution systems for synchronization of rf plants and/or lasers in short-pulse FEL facilities [11–13]. We have installed and are developing systems in the LCLS, and FERMI@Elettra.

Table 1: Beam Parameters used in FEL Simulations

Parameter	Value
Energy (GeV)	1.8
Peak current (A)	500
Slice transverse emittance (μm)	0.6
Slice energy spread (keV)	50
Length of core of bunch conditioned to lase (fs)	250
Range of energies within the core (keV)	±250

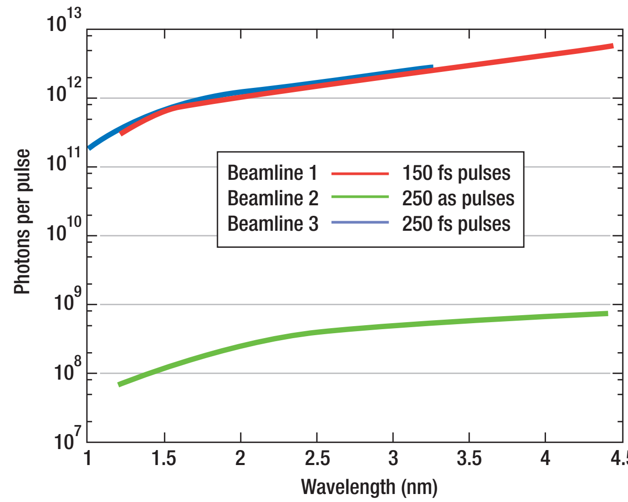

Figure 2: Beamline 1 is a seeded FEL shown here for 150 fs pulse duration; Beamline 2 is a 2-color attosecond beamline, here with 250 as pulses; Beamline 3 is a SASE FEL here with 250 fs pulses.

REFERENCES

[1] J. Corlett et al., "Design Studies for a Next Generation Light Source Facility at LBNL," FEL'10, Malmo, Sweden, August 2010, MOPA06

[2] J. Corlett et al., "Design Studies for a VUV–Soft X-ray Free-Electron Laser Array", *Synchrotron Radiation News* **22**, No. 5, 25 (2009).

[3] F. Sannibale et al, "Status of the LBNL normal-conducting CW VHF electron photo-gun," FEL'10, Malmo, Sweden, August 2010, WEPB36.

[4] C. F. Papadopoulos et al, "Photoinjector Beam Dynamics for the APEX Project," this conference, THP200.

[5] D. Filipetto et al, "Low Energy 6D Beam Diagnostic for APEX, the LBNL VHF Photo-injector," this conference WEP222.

[6] J. Feng et al, "Drive Laser System for APEX the Advanced Photo-injector Project at the LBNL," this conference, THP222.

[7] M. Venturini et al, "Studies of a Linac Driver for a High Repetition Rate X-rays FEL," this conference THP180.

[8] Stupakov, G., "Using the Beam-Echo Effect for Generation of Short-Wavelength Radiation." Physical Review Letters, 2009. 102(7): p. 074801.

[9] Zholents, A. and Penn, G., "Obtaining two attosecond pulses for X-ray stimulated Raman spectroscopy." NIM–A, 2010. 612(2): p. 254-259.

[10] G. Penn et al, "Seeded FEL Configurations for Soft X-ray Generation," this conference THP160.

[11] J.M. Byrd *et al*, *Proc. IPAC'10*, Kyoto, Japan, MOOCRA03.

[12] J.M. Byrd *et al*, *Proc. IPAC'10*, Kyoto, Japan, TUPEA033.

[13] R. Wilcox et al., Opt. Lett. 34, 3050 (2009).